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Models of human thermoregulation and the prediction of local and overall thermal sensations

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This study aims at comparing the predictions of skin temperature from different models of human thermoregulation and investigating the currently available methods for the prediction of the local and overall thermal sensations. In this paper, the Fiala model, the University of California, Berkeley (UCB) thermoregulation model and a multi-segmental (MS) Pierce model were tested against recently measured data from the literature. The local and overall thermal sensations were predicted for different room conditions, obtained from a recent experimental study, using the UCB comfort model coupled with the MS-Pierce model. The overall thermal sensation was further predicted using three other models. The predictions were then compared with the subjective votes obtained from that study. The equivalent temperature approach was also investigated based on the same experimental study. The results show comparisons of the predicted skin temperature by the thermoregulation models, under steady state and dynamic conditions, with the measured data as well as the predictions of the thermal sensations from the different models.

1. Introduction

Models of human thermoregulation have gained more importance with the concept of local thermal comfort. The local thermal sensation and comfort, corresponding to body segments, are mainly based on the local skin temperatures as stipulated in the concept of the equivalent (homogeneous) temperature [1]; and the University of California, Berkeley (UCB) comfort models [2]. Such models of human thermoregulation can be used to predict the local skin temperatures, along with other physiological variables, hence evaluating the local thermal sensation and comfort of individuals. Recent models of human thermoregulation are based on regression analysis for the simulation of active thermoregulation controls [3,4] or based on the approach that is given in Stolwijk model [5].

The Fiala model comprises the so called passive and active models [3,4]. The passive model consists of 15 spherical or cylindrical body elements and uses up to 7 different tissue materials. Most of the body parts are divided into anterior, posterior and inferior to account for asymmetries and hidden parts of the body. The passive model simulates the physical interaction between the human body parts and tissue layers as well as the interaction with the surrounding environment. The active model is based on statistical approach to simulate the human body's active controls such as the peripheral vasomotion, sweating and shivering heat production. The Fiala model contains lots of fine details, accounts for many different factors and is considered as a unique mathematical model of human thermoregulation.

The UCB thermoregulation model by Huizenga et al. [6] was developed on the basis of Stolwijk's model [5] and the research work by Tanabe [7]. In its original form, the model consists of 16 body segments but can be extended to have unlimited segmentation of body parts. The main modifications to the original Stolwijk (in addition to the segmentation) were: the improvement to the blood flow models including counter flow heat exchange at the limbs segments and perfusion from blood vessels to tissues; the addition of a clothing node to model the heat and moisture capacitances; the addition of heat transfer by conduction to surfaces in contact with the body; the improvement to the estimation of the convection and radiation heat transfer coefficients; the explicit radiation heat transfer calculation using angle factors; and the addition of a radiation heat flux model. As stated by the developers, the model is able to predict the core and extremity skin temperatures with reasonable accuracy under a range of environmental conditions.

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The multi-segmental (MS) Pierce model [8] was developed on the basis of the original 2-node Pierce model [9] using: measured data in neutral condition to adjust the local skin set-points and to calculate (using a line search method) the local core set-points that allow the model to predict the skin temperatures in the neutral condition with high accuracy; a modified calculation procedure for the convective heat transfer coefficients; and adjustment to the heat transfer term from core to skin using a common blood temperature along with local core temperatures. The model predictability of local skin temperatures was verified for sedentary activities using measured data under cold and warm conditions (maximum deviation was ±0.5 K). The model combines useful features such as the simplicity along with a good accuracy in estimating the local skin temperatures.

The application of these models has not yet been adopted by any of the international standards and guidelines as a possible prediction method for evaluating the local and overall thermal sensations. This may be related to the uncertainty for their predictability, the arguments of their validity and the limitations of their application.

The local thermal sensation (*LTS*), corresponding to different body segments, can be predicted using either the equivalent temperature approach (t_{eq}) or the UCB comfort model.

The t_{eq} approach was first introduced, for local body parts, by Wyon et al. [1] for assessing vehicle climate using a thermal manikin. Wyon and Sandberg [10] used the same approach for evaluating the local thermal discomfort due to vertical temperature gradients in buildings. Thereafter, the approach was used in several other studies for the evaluation of thermal comfort in buildings such as Tanabe et al. [11]. The t_{eq} is presented on a diagram that shows the so called ideal profile (neutral) and acceptable ranges (mean vote = ±0.8 corresponds to 20% dissatisfied) for the different body parts. A new diagram with a wider acceptable ranges (mean vote = ±1.5) was later obtained by Nilsson [12] from subjective votes in more than 30 sets of climatic conditions given in Nilsson's thesis [13]. The t_{eq} at these conditions was estimated using two thermal manikins and correlated with the subjective votes from the human subjects' tests. The t_{eq} approach originally suggests whether the body segments are in comfort or discomfort thermal condition without referring to predictions of *LTS* votes.

The UCB comfort model [2] was based on a large-scale experimental work at the University of California, Berkeley. This is a rational model for the estimation of local thermal sensation. The model has a static term that is based on the deviation of the local skin temperature from its set-point and a dynamic term based on the time derivative of the skin and core temperatures. The UCB comfort model is not a stand-alone model and needs coupling with a model of human thermoregulation or to be fed with a measured data. The UCB comfort model was validated using measured data and subjective votes in vehicle environment. However, the performance of such a model needs to be verified more extensively for different cases especially when coupled with a thermoregulation model.

In this study, three models of human thermoregulation mentioned above were used to predict the local skin temperatures for different test conditions found from the literature [8,14–16] and the predictions were compared with the measured data. The MS-Pierce model was then coupled with the UCB comfort model (P-UCB) to predict the local and overall thermal sensation at different room conditions from a recent experimental study by Cheong et al [17]. The predictions were compared with the subjective votes given in that study. The comparisons included the equivalent temperature approach represented with its suggested comfort zone diagram as given in [12]. In addition, the P-UCB model was used to predict the thermal sensations for the conditions given in Nilsson's thesis [13]. Furthermore, the overall thermal sensation was estimated for the test conditions given in Cheong's study [17] using additional three models: *PMV* index [18]; DTS model [19]; and Nilsson's model [12]; and the predictions were compared with the subjective votes.

2. Methods

The strategy of the study was to compare the predictability of skin temperature from different thermoregulation models and hence evaluating the local and overall thermal sensations using the currently available models. Table 1 presents the used models, its predicted variable and the reference experimental data.

2.1. Models of human thermoregulation

The Fiala model [3,4], UCB model of thermoregulation [6], and the MS-Pierce model [8] were tested with respect to the predictability of skin temperature and against recently measured data from the literature. The detail description of the simulated conditions represented by 5 recent measurements under steady-state [8,14,15] and dynamic [16] conditions are presented in Section 2.4.1. The prediction of the skin temperature under the dynamic condition was carried out using only the Fiala and the MS-Pierce models. The input data for these conditions were similarly used in the 3 models. This included the clothing and activity levels; indoor conditions; and the temperatures of the room surfaces or radiant temperatures at different levels.

2.2. Local thermal sensation models

Two known methods for evaluating the local thermal sensation (*LTS*) of individuals (i.e. the t_{eq} approach and the UCB comfort model) were used to predict the *LTS* for 15 test conditions from a recent experimental study [17]. The UCB comfort model was coupled with the MS-Pierce model (P-UCB) in these predictions. In addition, the P-UCB model was used to predict the *LTS* for 16 test conditions given in Nilsson's thesis [13].

The t_{eq} approach is represented in this comparison by the suggested comfort zone diagram (clothing independent diagram) in Nilsson's study [12]. In that study, a model for each body segment was obtained using linear regression, to construct the diagram, in the following form:

$$t_{eq} = T_{sk} - R_T^*(a + b^*LMV) \quad (1)$$

where T_{sk} is the manikin skin temperature (°C), R_T is the total thermal insulation resistance(m^{2}K/W), a and b are the regression coefficients (W/m^2), *LMV* is the local mean thermal vote at the body part or zone (based on Bedford thermal sensation scale). As stated by Nilsson [12], the equation is valid for total clothing insulation

Table 1
The models in the scope of the comparisons.

Model	Predicted variable			Compared with experimental data from
	Skin temp. (T_{sk})	LTS	OTS	
Fiala Thermoregulation [3,4]	x			[8,14,15,16]
Fiala DTS model [19]			x	[17]
MS-Pierce Thermoregulation [8]	x			[8,14,15,16]
Nilsson [12]		x	x	[17]
P-UCB		x	x	[13,17]
PMV [18]			x	[17]
UCB Thermoregulation [6]	x			[8,14,15]
UCB Comfort [2]		x	x	[13,17]
UCB Comfort [21]			x	[17]

(R_T) values between 0.9 and 1.9clo for a whole seated body. Nilsson's model (Eq. (1)) was used to predict the *LTS* (*LMV*) for the indoor conditions given in [17] by substituting the thermal insulation values and estimating the t_{eq} from the test conditions using an empirical equation given by Madsen et al. [20].

The UCB comfort model [2] can be represented by the following formula:

$$LTS = 4*\left(\frac{2}{1+EXP(-C_1*(T_{skin,local}-T_{skin,local,set})-K_1*((T_{skin,local}-T_{skin,local,set})-(T_{skin,mean}-T_{skin,mean,set})))}-1\right) + C2_i\frac{dT_{skin,local}}{dt}+C3_i\frac{dT_{core}}{dt} \quad (2)$$

where *LTS* is the local thermal sensation (based on ASHRAE 9-point scale); C_1 is a coefficient with a value from 0 to 1 that varies for different body parts; $T_{skin,local}$ is the local skin temperature (°C); and $T_{skin,local,set}$ is its set-point (°C); K_1 is a coefficient with a value from 0 to 1 that varies for different body parts; $T_{skin,mean}$ is the mean skin temperature (°C); and $T_{skin,mean,set}$ is its set-point (°C); $C2_i$ and $C3_i$ are the thermal capacities at the skin and core nodes respectively.

2.3. Overall thermal sensation models

In this study, the overall thermal sensation (*OTS*) was estimated for 15 different conditions given in Cheong's study [17] using 4 different methods. These included the *PMV* index [18], the P-UCB model based on Zhang's thesis [2], the dynamic thermal sensation (DTS) model [19], and using Nilsson's model (Eq. (1)) for whole body [12]. In addition, the *OTS* was estimated by the UCB model [2] using directly the subjective *LMV* values. The comparison also included predicted votes for the same cases by the new UCB model [21].

PMV is calculated from:

$$PMV = \left(0.352*EXP\left(-0.42\frac{M}{A_{Du}}\right)+0.032\right)*\left\{\frac{M}{A_{Du}}(1-\eta)-0.35*\left[\begin{matrix}43-0.061\frac{M}{A_{Du}}(1-\eta)\\-p_a\end{matrix}\right]-0.42\left[\frac{M}{A_{Du}}(1-\eta)-50\right]\right.$$
$$\left.-0.0023\frac{M}{A_{Du}}(44-p_a)-0.0014\frac{M}{A_{Du}}(34-t_a)-3.4*10^{-8}f_{cl}*\left[(t_{cl}+273)^4-(t_{mrt}+273)^4\right]-f_{cl}h_c(t_{cl}-t_a)\right\} \quad (3)$$

where A_{Du} is Dubois body surface area (m^2), η is the external mechanical efficiency, p_a is the water vapor pressure (Pa), M is the metabolic rate (kcal/h), t_a is the air temperature (°C), t_{cl} is the clothed body surface temperature (°C), t_{mrt} is the mean radiant temperature in relation to a person at a given location (°C).

The UCB model [2] estimates the overall sensation by weighting the *LTS* from different body segments. The model may be expressed by the formula:

$$OTS = \frac{\sum weight_i.LTS_i}{\sum weight_i} \quad (4)$$

where i denotes different body segments, $weight_i$ is calculated from:

$$weight_i = a*(LTS_i - \overline{LTS_i}) \quad (5)$$

where a is the slope of the linear model, $\overline{LTS_i}$ is averaged local sensation (arithmetic mean of LTS_i).

The new UCB model [21] uses a different approach that involves different calculation procedures at different conditions and introduces the so called no-opposite and opposite sensation models. Zhang et al. [21] calculated the predicted *OTS* votes for the test conditions in [17]. The predictions were obtained directly from that study and were presented in this comparison.

Fiala's DTS model calculates the dynamic thermal sensation and accounts for the changes of the core and skin temperatures in steady-state and dynamic situations. The model can be expressed by the following formula [19]:

$$DTS = 3*\tanh(f_{sk}+\Phi+\Psi) \quad (6)$$

where f_{sk} is a function that accounts for the effect of the deviation between the skin temperature and its set-point, Φ accounts for the effect of core temperature, and Ψ accounts for the dynamic changes in core and skin temperatures on the thermal sensation.

2.4. Experimental data

2.4.1. Skin temperature measurements

Measured data of local skin temperatures under steady-state and dynamic conditions was obtained from recent studies [8,14–16].

Foda and Sirén [8] conducted skin temperature measurements at 24 body sites under uniform warm (Case 1) and cold (Case 2) conditions. Eleven human subjects that participated in those experiments carried out sedentary activities and wore normal office clothes with an intrinsic thermal insulation value of 0.6 clo, (clo = 0.155m^2°C/W). These experiments investigated the human body response due to a temperature step change and studied the variability in skin temperatures for tests with different durations on the same subjects, as well as the physiological steady-state temperatures under different conditions. The room temperatures in Case 1 and Case 2 were at 30 °C and 15 °C respectively. In Case 2, the relative air velocity (at 0.6 m level) was 0.14 m s^{-1} whiles it was a calm condition in Case 1 at which the relative air velocity was less than 0.05 m s^{-1}.

Sakoi et al. [14] investigated the skin temperature distribution in the sitting posture under various asymmetric thermal conditions. A total of 12 human subjects (males and females) participated in 35 different asymmetrical cases. The subjects were sitting in a booth wearing only underwear clothes. The tests included several cases of up-down, right-left and front-back asymmetric conditions. Two cases (Case 3 and Case 4) are presented in this paper corresponding to test conditions nos. 9 and 28 respectively. In the two cases, the relative air velocity was less than 0.05 m s^{-1} while the air temperature was kept at 28 °C. In Case 3 (front-back asymmetry), the front panel temperature was at 42 °C while the back panel was at 14 °C. In case 4 (up-down asymmetry), the upper panel was at 21 °C while the lower panel was at 35 °C.

Almesri and Awbi [15] investigated the performance of two ventilation systems which use air mixing and displacement ventilation methods. In that study, measurements of local skin temperature were carried out using 8 human subjects in a nearly neutral condition (Case 5). The room temperature was controlled at 25.5 °C with 40% relative humidity (*RH*) and relative air velocity of 0.1 m s^{-1}. The subjects had sedentary activities during the tests and wore clothing ensembles with an intrinsic thermal insulation value of 0.87 clo.

Amunir et al. [16] carried out measurements in which 10 male subjects wore only shorts and were exposed to stepwise temperature changes over 150 min under different environmental conditions. The measurements aimed at evaluating the dynamic performance of the Stolwijk's model [5]. The phases of the step change were in the sequence neutral-cold-neutral-warm-neutral. The room temperature was 29.4 °C, 19.5 °C and 38.9 °C in the neutral, cold and warm conditions respectively.

2.4.2. Subjective assessments of indoor conditions

The prediction of the *LTS* and *OTS* was carried out using the P-UCB model and Nilsson's model (Eq. (1)) for the test conditions in Cheong's study [17]. In that study, Cheong et al. investigated the thermal sensation and comfort in an environment served by displacement ventilation. Sixty human subjects (30 males and 30 females) participated in a total of 15 tests, carried out sedentary activities and wore clothing ensembles with an intrinsic thermal insulation value that varied from 0.63 to 1.15 clo for the different tests. The local thermal insulation values were estimated based on the described garments using ISO9920:2007 [22]. The subjects were allowed to adjust their clothing for the first 9 cases. The room temperature was controlled at 20, 23 and 26 °C with a vertical gradient of 1, 3 and 5 K/m for each room temperature. The test duration was 3 h and the human subjects voted on ASHRAE and Bedford 7-point scales every 30 min. The ASHRAE scale was used to assess the thermal sensation while the Bedford scale was used for comfort. The average relative air velocity (*v*) was kept below 0.1 m s^{-1} for the different cases. The relative humidity was in a range from 50 to 54% for all cases.

The prediction of the *LTS* was also carried out using the P-UCB model for 16 test conditions given in Nilsson's thesis [13]. These tests were used in the construction of Nilsson's model [12]. The given experimental data includes the segmental t_{eq} along with the *LMV* values for the different conditions. The tests involved various asymmetrical thermal conditions. Asymmetries were produced by vertical air temperature gradients and solar radiation. The twenty male subjects who participated in the experiments wore summer clothing ensembles ($R_T = 1.3$ clo). The test duration was 1 h in which the subjects voted twice on the Bedford scale once every 30 mins. The comparison between the predictions by the P-UCB model and the *LMV* from Nilsson's thesis [13] may seem irrelevant since the UCB model is based on an extended ASHRAE scale as illustrated in Fig. 1. However, the authors were encouraged to apply this comparison due to the favorable performance of the two models (i.e. P-UCB, Nilsson) for the conditions in Cheong's study [17] and the very minor differences between the subjective voting on both scales in that study. Such a comparison may also be justified by McIntyre's [23] statement that both scales behave in a similar way and the authors believe that it should be acceptable at least for the scale range ±1 which refers to comfortable sensation on both scales.

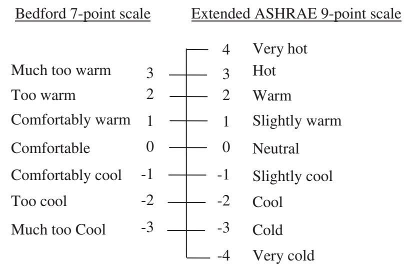

Fig. 1. Bedford 7-point scale and the extended ASHRAE 9-point scale.

3. Results and discussion

3.1. Predictability of the thermoregulation models

The comparisons of the predicted steady-state skin temperatures using the different models are shown along with the measured data in Figs. 2–5. In general, the three models showed very reasonable predictability. The MS-Pierce and the Fiala models had relatively higher predictability, for all test conditions, than the UCB model. The MS-Pierce model had the lowest average absolute deviation (AAD) from the measured data for the 5 cases. Table 2 gives the AAD values and the standard deviation (SD) from the measured data for the predictions by the 3 models. The comparison can be considered comprehensive as it includes different levels of clothing, a wide range of uniform neutral, warm and cold conditions, as well as cases under asymmetrical thermal conditions. However, the comparison is limited to seated persons carrying out sedentary activities.

The dynamic performance of the MS-Pierce model along with the Fiala model was tested against the measured data given in Munir's et al. study [16]. Fig. 6 shows the variation of the calculated and measured skin temperatures with time. The step changes are denoted on the figure with capital letters from A to E where A, C and E denote the neutral condition (29.4 °C); B denotes the cold condition (19.5 °C); and D denotes the warm condition (38.9 °C). In general, the MS-Pierce showed relatively better predictions than the Fiala model when compared to the measured data. For most body parts, the dynamic performance of the two models is in good agreement (max. deviation ≈ 1 K) with the measured data. For few body segments (e.g. Thigh), the maximum deviation between the measured data and the predicted temperatures by the two models was close to 2 K. The maximum deviations were mainly during the step change from B to C at which the rate of change in the measured body temperatures was

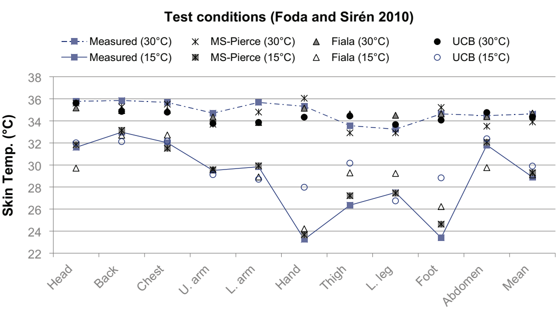

Fig. 2. Comparison between predicted skin temperature and measured data for warm and cold conditions, Cases 1 and 2.

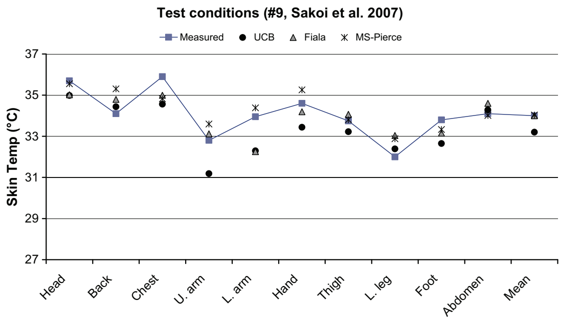

Fig. 3. Comparison between predicted skin temperature and measured data in front-back asymmetric condition, Case 3.

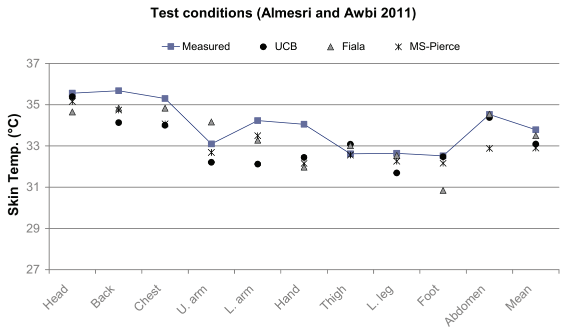

Fig. 5. Comparison between predicted skin temperature and measured data for uniform neutral condition, Case 5.

mostly steeper. The deviations at the first step (A) were partly from the models' startup phase and starting values.

3.2. Estimation of thermal sensation

The MS-Pierce model was selected for coupling with the UCB comfort model (P-UCB) for the estimation of the thermal sensations as it produced higher predictability of skin temperature than the other two models (Fiala and UCB) as discussed earlier. The estimation of the *LTS* was carried out using the P-UCB model and Nilsson's model (Eq. (1)) for the 15 different cases given in Cheong's study [17] and was compared with the subjective *LMV* values given on the ASHRAE and Bedford scales. Fig. 7 shows the estimated *LTS* along with the *LMV* values. As can be seen, the predictions by both models were nearly in agreement for most body segments (i.e. back, chest, arm, thigh and leg). The discrepancies between the predictions by both models and the *LMV* values varied for the different body segments. The predicted values were more close to the *LMV* values for the lower body segments (e.g. thigh, leg). The discrepancies with the *LMV* values may, to a small extent, be related to the estimation of the local clothing values for the upper body segments, the assumed metabolic rate (i.e. 65 W/m^2) and to the models' predictability for tropically-acclimatized subjects.

The subjective *LMV* values in Cheong's study [17] on the ASHRAE and Bedford scales were nearly identical and the predictions by the two models were nearly in agreement for most body parts. Thus, the authors were encouraged to test the P-UCB model against 16 different

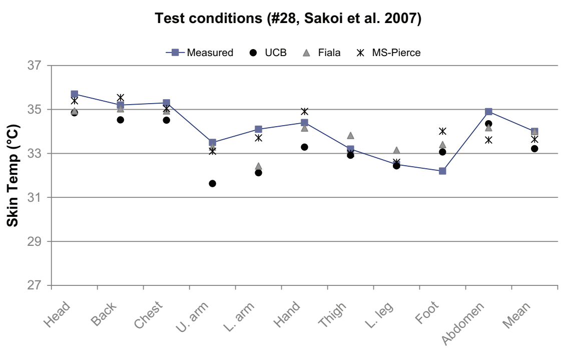

Fig. 4. Comparison between predicted skin temperature and measured data in up-down asymmetric condition, Case 4.

cases used by Nilsson [13] in constructing his model (Eq. (1)). Fig. 8 shows the estimated *LTS* for the body segments by the P-UCB model compared with the subjective *LMV* values. The estimated *LTS* by the P-UCB model were nearly in agreement (especially at the higher t_{eq} levels) with the *LMV* values for the same body parts mentioned in the first comparison. For these body segments, the discrepancies between the estimated *LTS* and the *LMV* values increased at the lower levels of t_{eq}. The discrepancies at these levels may be related partly to the different sensation scales in that range. The estimation of the *LTS* by the P-UCB model showed large discrepancies with the *LMV* values for the head, hand and foot segments. The main discrepancies were at the cold side at which the P-UCB model predicted considerably lower values of *LTS*.

The comparison between the estimated *LTS* by the P-UCB model and Nilsson's model (Eq. (1)) is mainly to indicate the differences between the two available methods for such a prediction (i.e. the equivalent temperature approach and the UCB comfort model). Generally the two methods can provide a nearly similar assessment of the local thermal sensation for some body parts. The UCB comfort model has a variable profile (relies on the skin temperature) at each room condition and involves the whole body effect on the local sensations. The output from the UCB comfort model depends on the skin temperatures predicted by a thermoregulation model. Therefore, the accuracy of its estimations is partly influenced by the predictability of the used thermoregulation model. Nilsson's model suggests an equally distributed profile for the sensation at different t_{eq} for each segment. While it includes the clothing effect, it does not include physiological or physical effects of the human body on the sensation. The model is limited for a seated person carrying out sedentary activities based on a sample of measured data.

The overall thermal sensation (*OTS*) was estimated for the cases given in Cheong's study [17] using the P-UCB model that is based on the UCB model [2], *PMV* index calculations [18], Fiala's DTS model [19], Nilsson's model for whole body [12] and the UCB model [2] using directly the *LMV* values. The predictions by these

Table 2
Models' average absolute deviation (K) from the measured data and the standard deviation.[a]

Model	Case 1	Case 2	Case 3	Case 4	Case 5
UCB	0.7 (0.5)	1.7 (1.9)	0.9 (0.5)	0.9 (0.6)	0.9 (0.7)
Fiala	0.7 (0.6)	1.3 (1.0)	0.7 (0.5)	0.6 (0.5)	0.8 (0.7)
MS-Pierce	0.3 (0.2)	0.3 (0.2)	0.5 (0.4)	0.5 (0.5)	0.8 (0.6)

[a] Values in brackets refer to the standard deviation.

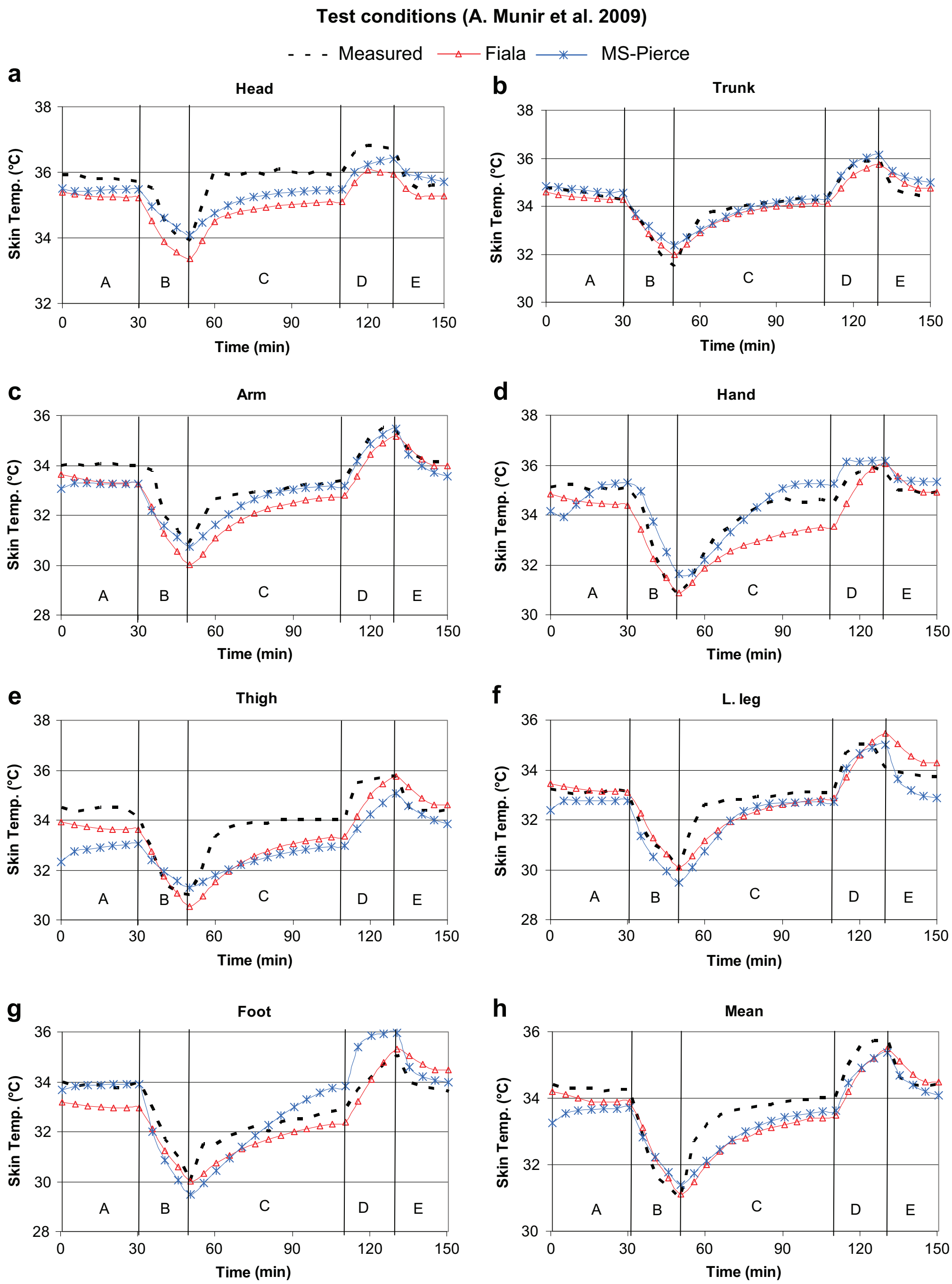

Fig. 6. Comparisons between the dynamic performance of the Fiala and MS-Pierce models with measured data.

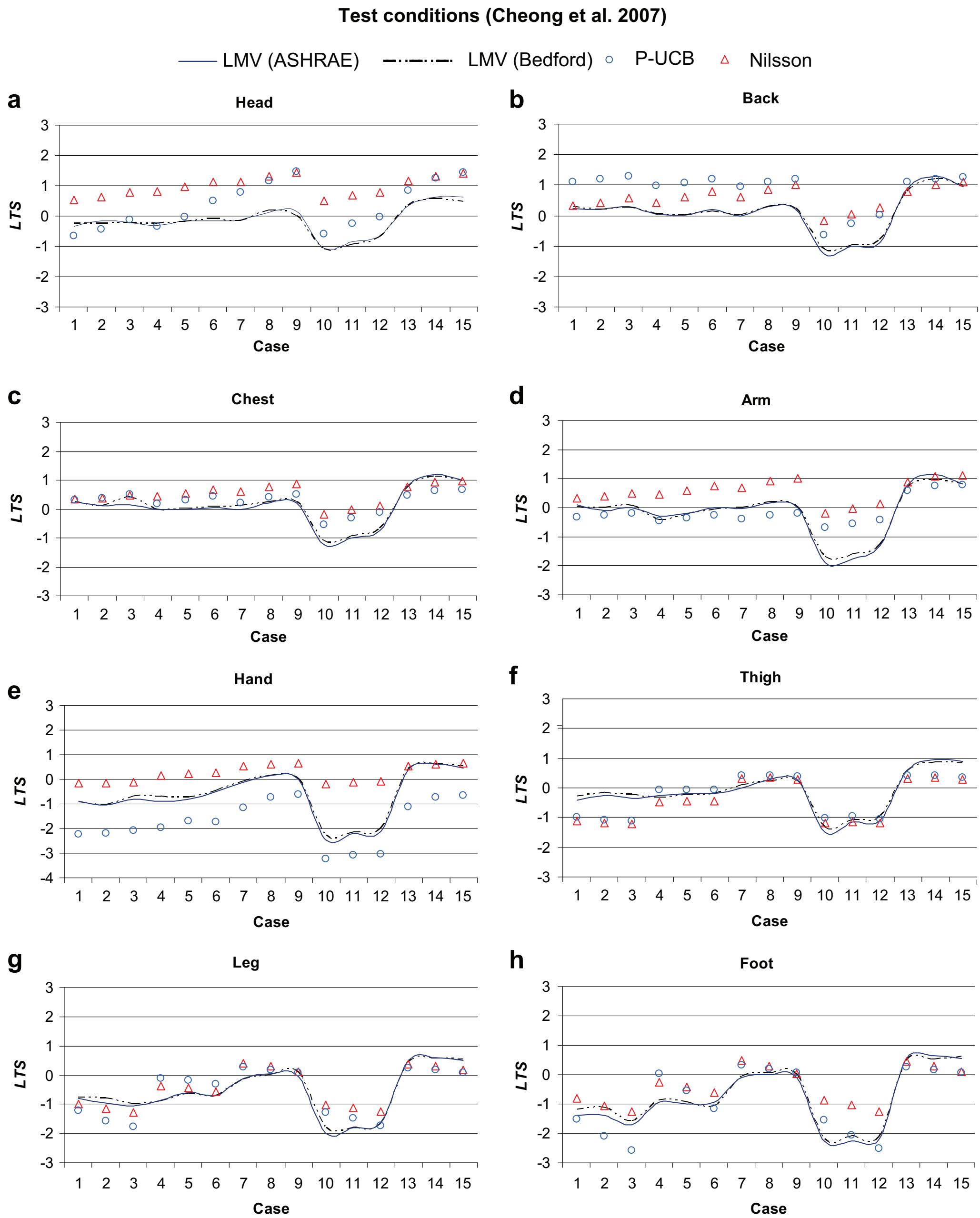

Fig. 7. Comparison between the estimated local sensations and the subjective votes.

different models were nearly in agreement for most cases with discrepancies less than 1 on the scale. The discrepancies with the subjective votes varied for these models and increased for the Cases 10-12. For these cases, the predicted *OTS* by the UCB model [2] (using directly the *LMV* values) show discrepancies from 0.8–0.9 on the scale. This may explain the poor prediction by the P-UCB model for those cases which is partly due to the comfort model structure. The prediction of the *OTS* by the P-UCB model is based on the predicted *LTS* votes by weighting their effects on whole body state while the other models (i.e. *PMV*, DTS and Nilsson) predict the *OTS* based on mean physiological variables or a separate formula. Although the first approach seems more logical, in this comparison it mostly showed the highest discrepancy with the actual votes. Generally, the lower prediction of the

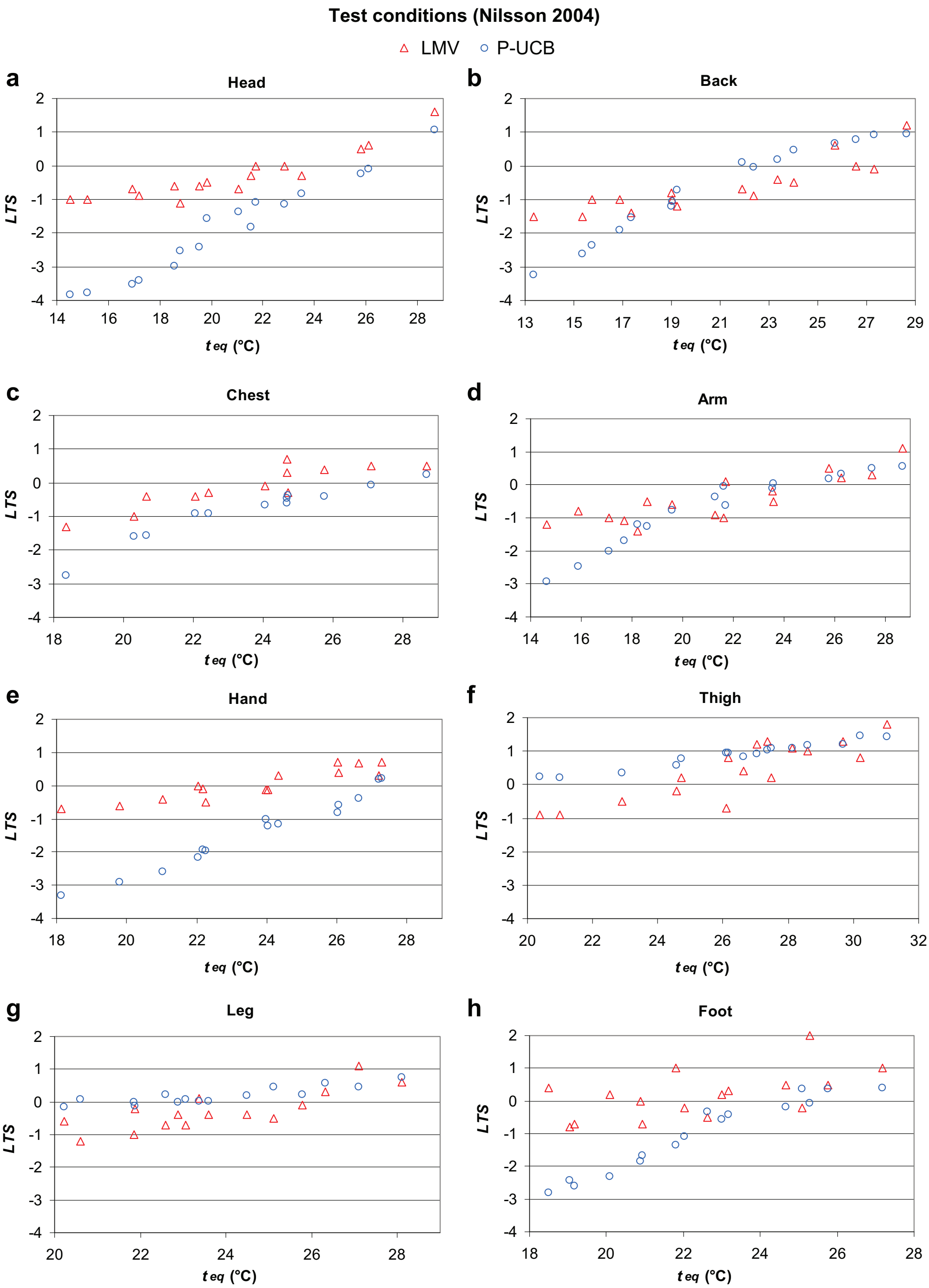

Fig. 8. Comparison between the estimated local sensations and the subjective votes.

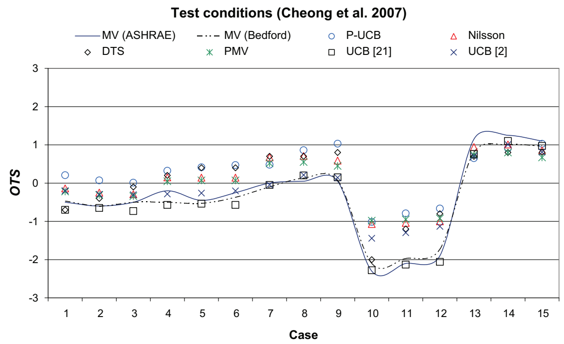

Fig. 9. Comparison between the estimated overall sensations from different models and the subjective votes.

thermal sensation for 15 different indoor conditions from a recent study. The predictions by the coupled model (P-UCB) along with Nilsson's model (based on the t_{eq} approach) were compared with the subjective votes from these 15 conditions. The predictions by the two models were nearly in agreement for most body segments. The discrepancies with the subjective votes varied under the different indoor conditions and were generally within reasonable limits. The P-UCB model was further used to predict the thermal sensation for 16 indoor conditions from the literature. The results were nearly in agreement with the subjective votes for most body segments. The discrepancies between the predictions and the subjective votes increased for the head, hand and foot segments especially under cold conditions. In addition, the prediction of the overall thermal sensation was carried out using four different models (i.e. *PMV* index; UCB comfort model; DTS model, Nilsson's model) for the same 15 indoor conditions. The results showed variations in the predicted votes by these models (<1 on the scale).

Table 3
Predicted *OTS* by the different models.

Cases	MV (ASHRAE)	MV (Bedford)	P-UCB	DTS	Nilsson	PMV	UCB [2][a]	UCB [21][b]	Max	Min	Average
1	−0.50	−0.47	0.21	−0.70	−0.14	−0.22	−0.20	−0.70	0.21	−0.70	−0.21
2	−0.60	−0.60	0.07	−0.40	−0.25	−0.31	−0.29	−0.65	0.07	−0.40	−0.24
3	−0.50	−0.50	0.01	−0.10	−0.29	−0.34	−0.30	−0.73	0.01	−0.34	−0.20
4	−0.20	−0.50	0.32	0.20	0.15	0.05	−0.28	−0.57	0.32	−0.28	0.09
5	−0.45	−0.53	0.41	0.40	0.14	0.07	−0.26	−0.54	0.41	−0.26	0.15
6	−0.25	−0.37	0.47	0.40	0.14	0.07	−0.20	−0.57	0.47	−0.20	0.18
7	0.00	−0.10	0.48	0.70	0.67	0.52	−0.04	−0.05	0.70	−0.04	0.47
8	0.05	0.13	0.86	0.70	0.71	0.55	0.21	0.20	0.86	0.21	0.61
9	0.05	0.07	1.03	0.80	0.59	0.45	0.14	0.15	1.03	0.14	0.60
10	−2.30	−2.10	−1.01	−2.00	−1.07	−0.98	−1.44	−2.28	−0.98	−2.00	−1.30
11	−2.10	−1.97	−0.79	−1.20	−1.04	−0.95	−1.30	−2.13	−0.79	−1.30	−1.05
12	−1.90	−1.73	−0.66	−0.80	−1.00	−0.92	−1.13	−2.06	−0.66	−1.13	−0.90
13	1.15	0.80	0.65	0.70	0.94	0.74	0.71	0.76	0.94	0.65	0.75
14	1.25	1.00	0.91	0.80	1.01	0.80	1.01	1.10	1.01	0.80	0.91
15	1.10	0.97	1.03	0.80	0.85	0.67	0.81	0.97	1.03	0.67	0.83
AAD			0.73	0.55	0.50	0.53	0.24	0.16			
SD			0.36	0.27	0.31	0.34	0.17	0.12			

[a] Calculated using the actual *LMV* values.
[b] Obtained directly from [21] and it was calculated there using the actual *LMV* values.

OTS by all these models may be partly related to the assumed metabolic rate and the models' predictability for tropically-acclimatized subjects. Fig. 9 shows the estimated *OTS* values by the models mentioned above plus the predicted values by Zhang et al. [21] using directly the *LMV* values for the same cases in validating their new *OTS* model [21]. As stated in that study, the new model was introduced to improve the predictability of the *OTS* model [2]. However, the new model involves several calculation procedures and seems complex to apply in practice. Table 3 shows the predicted votes by these 5 methods plus values from Zhang's study [21], the min, max and average as well as the standard deviation (SD) values from the 5 methods for the different cases. The average absolute deviation (AAD) and the SD for each method are also shown in the table.

4. Conclusions

Three models of human thermoregulation (i.e. Fiala, UCB and MS-Pierce models) were tested against recently measured data from the literature under steady-state and dynamic conditions. The MS-Pierce model had the best predictability (average absolute deviation ranged from 0.3 to 0.8 K) in steady-state and showed very good performance in the comparisons for the dynamic condition along with the Fiala model. Therefore, the MS-Pierce was selected for coupling with the UCB comfort model to predict the local The discrepancies between these models and the subjective votes varied for the different conditions and were in average within 1 on the scale. The results of the local and overall thermal sensations from different models were compared to investigate the variations of their predictions without referring to any particular model or subjective votes study as a benchmarking.

Future work will include adapting a comfort model in combination with the MS-Pierce model and integrating it with a CFD code to assess the thermal comfort in non-uniform environments.

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